Water Quality Additions to CASC2D – TAPS

by Patrick N. Deliman, Terry K. Gerald, and Carlos E. Ruiz

PURPOSE: The purpose of this effort was the implementation of nutrient water quality components included in the Transport and Pollutant System (TAPS) into the CASC2D hydrology watershed model. The CASC2D model is still in development and is being improved, refined, and updated with new technology. Users of CASC2D need to have a thorough background in hydrology and numerical modeling. CASC2D is currently being restructured and an updated version (under a new name, Generalized Surface/Subsurface Hydraulic Analysis (GSSHA)) is anticipated in the near future. This newly updated version of the CASC2D code will replace the version of CASC2D in the Watershed Modeling System (WMS).[1]

BACKGROUND: The CASC2D code was originally developed by Prof. Pierre Y. Julien at Colorado State University. Prof. Julien initially formulated a two-dimensional overland flow routing algorithm written in APL. The overland flow routing module was converted from APL to FORTRAN by Dr. Baharm Saghafian, then at Colorado State University with the addition of Green & Ampt infiltration and explicit channel routing (Julien and Saghafian 1991; Saghafian 1992; Julien, Saghafian, and Ogden 1995). The FORTAN version was reformulated, significantly enhanced, and rewritten in the C programming language by Dr. Bahram Saghafian at the U.S. Army Construction Engineering Research Laboratories.

CASC2D is a physically based, distributed parameter hydrologic model that simulates hydrologic responses within a watershed based on precipitation records. The model solves the two-dimensional diffusive wave equation. The code potentially offers an improved alternative to the traditional lumped parameter empirically based models by taking into account the existing spatial variability that exists within a typical watershed. Processes simulated in CASC2D include interception, infiltration, redistribution, evapotranspiration, surface runoff routing, and channel routing.

PROJECT & OVERVIEW: A new nutrient modeling code, TAPS, was derived from the SWAT (Soil & Water Assessment Tool) watershed model and the EPIC (Erosion/Productivity Impact Calculator) model (Arnold et al. 1995, Sharpley and Williams 1990). The current state of the nutrient modeling code that has been coded and placed into CASC2D will be described and potential areas for additional research will be discussed. Brief overviews of SWAT and EPIC follow.

SWAT: The Soil and Water Assessment Tool (SWAT) model is the latest model developed by the USDA-ARS (Arnold et al. 1995). SWAT was developed as a basin scale model. Complete flow and contaminant routing are accomplished and GIS interfaces, a weather generator, lake water quality, and water management options are included.

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[1] Personal Communication, 1999, W. D. Martin, Coastal and Hydraulics Laboratory, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Runoff is estimated from daily rainfall data using the SCS curve number method. Peak runoff is computed using a modification of the rational method. Time to concentration for both channels and overland flow is estimated with Manning's formula. Percolation and lateral subsurface flow are computed together and are based on storage routing and kinematic routing. Groundwater flow is simulated based on a shallow aquifer model with evaporation, pumping, seepage, and discharge being included. The daily water balance includes evapotranspiration based on Hargreaves, Priestley-Taylor, or Penman-Monteith equations. Plant transpiration is based on the Ritchie model. Transmission losses in channels are considered along with ponds and other small structures that will reduce runoff quantity (Arnold et al. 1995). Water may be transferred from one portion of the watershed to another to simulate pumping and irrigation. Channel flow is routed by the Williams variable storage coefficient method. Water entering lakes or reservoirs utilizes a specified volume balance approach.

Sediment yield is based on the Modified Universal Soil Loss Equation. Nitrogen, phosphorus, and pesticides are simulated using the CREAMS/GLEAMS (Knisel 1993) models including biochemical processes and groundwater loading. During runoff events, chemical degradation is not simulated in the channels, but a two-dimensional lake water quality model has been added to simulate lake processes. Sediment-bound chemicals may settle and be detached in channels. Crop growth simulators are included to account for changing ground cover and plant uptake of nutrients. Point sources may also be included in the simulations (Arnold et al. 1995).

SWAT includes a weather generator similar to the one used in EPIC and SWRRB for long-term simulations and numerous weather station locations to reduce user input (Arnold et al. 1995). Weather may be simulated for the entire basin or for each subwatershed individually as is done in SWRRB (Arnold and Williams 1994). SWAT also includes an interface with GRASS GIS (Arnold et al. 1995). This allows the user to easily input data from a large heterogeneous basin. One feature in SWAT not seen in any other model is the mixing of watershed delineation techniques. A grid system may be used in areas of special interest, while the rest of the basin may be simulated as more homogeneous subwatersheds. This allows detailed simulation of areas of interest without a large increase in input data (Arnold et al. 1995).

SWRRB and ROTO have both been extensively tested. SWAT has been applied to several gauged watersheds and rendered good results (Arnold et al. 1995).

EPIC: Concerns over the possible decrease in agricultural productivity due to soil loss prompted the creation of the Erosion/Productivity Impact Calculator (EPIC). EPIC was developed to determine the long-term productivity of soil using various management strategies (Williams 1994, Dumesnil 1993). EPIC simulations are usually done on small areas over a long period of time. Since the model's main purpose is to compute productivity, a greater portion of the model deals with crop growth compared to other models, but water yield, sediment production, and nutrient removal are also considered (Williams 1994).

The hydrology component of the model is based on a daily water balance. Surface runoff is based on the SCS curve number method and the peak runoff rate is estimated by the rational formula. Percolation is computed using a storage routing technique to predict flow through each soil layer. Once water has percolated past the root zone, it is considered groundwater and lost from the model. Lateral subsurface flow is computed for each soil layer using a kinematic storage model starting at the top

layer and progressing downward. Soil evaporation may be computed using either the Penman method or the Priestly-Taylor method. Plant evapotranspiration is based on the Ritchie method and requires the leaf area index depending on the stage of crop growth. Snowmelt and transmission losses are also taken into account. Since EPIC is a field-scale model, channel routing is not considered. Irrigation of crops may be considered with the daily water balance (Williams 1994, Sharpley and Williams 1990).

Sediment yield in EPIC may be computed in one of three ways specified by the user, Universal Soil Loss Equation (USLE), Modified USLE (MUSLE), or the Onstad-Foster modification of the USLE. Erosion from furrow irrigation is always computed using MUSLE. The variation between these models is the energy factor used to drive erosion, where USLE uses rainfall only, MUSLE uses runoff only, and Onstad-Foster uses a combination of rainfall and runoff. As sediment leaves the field, the surface layer of soil is reduced in thickness. Erosion continues to move through the soil profile, allowing for soil weathering (Williams 1994, Sharpley and Williams 1990). Wind erosion is computed, but washoff does not affect runoff sediment loads (Sharpley and Williams 1990). Losses of nitrate are considered from the top layer of soil only. Nitrate that is adsorbed and in solution may leave with the runoff. Nitrate in solution may also leave the field through percolation or lateral subsurface flow. Loading functions for organic nitrogen are also provided. Nitrogen may be moved into the top soil layer as water in that layer evaporates and water from lower layers enters. The nitrogen cycle is simulated by the processes of denitrification, mineralization, immobilization, and fixation. The concentration of nitrogen in rainfall may also be included. Phosphorus is transported in solution or with sediment. The phosphorus cycle includes mineralization, immobilization, and mineral cycling. EPIC does not track pesticide losses (Williams 1994, Sharpley and Williams 1990).

EPIC is able to generate long-term sediment predictions because of its built-in weather generator and weather database (Sharpley and Williams 1990). Rainfall timing is based on the probability of a wet day following a dry day and a wet day following a wet day. Daily rainfall amounts are predicted using a skewed normal distribution with the mean rainfall and standard deviation for the month. Air temperature and solar radiation are correlated with rainfall. Wind speed is predicted from a two-parameter gamma distribution and direction is based on a cumulative probability distribution. Daily relative humidity is arrived at using the monthly average and a triangular distribution and adjusting for a wet or dry day. Soil temperature and soil pH are also computed and applied to the nutrient cycle. EPIC includes a crop growth simulator to account for various stages of crop growth and their impacts such as nutrient uptake, transpiration, and soil residue. An economic section is included to further assess soil productivity (Williams 1994, Sharpley and Williams 1990).

EPIC has been used to simulate many different things, including soil productivity, crop growth, and soil degradation (Dumesnil 1993). Sharpley and Williams (1990) report on the validation of the model components and application of the complete model to differing soils and climates. Sensitivity analysis was also reported.

METHODS: A detailed and lengthy examination of the SWAT and EPIC model codes indicated it would be very impractical to perform a cut-and-paste implant of their code into CASC2D. SWAT and EPIC are both written in FORTRAN, while CASC2D is written in C. A FORTRAN-to-C translation of SWAT or EPIC, while possible, would have yielded an incongruent design when placed

within CASC2D. Note that the SWAT and EPIC codes are much larger than CASC2D and a lot of extra "baggage" would have come with a code transfer.

Adding water quality and nutrient modeling capabilities to CASC2D required the development of a three-tier water quality component model with an inclusive hierarchal data structure corresponding to each component model. The water quality component models consist of an aquatic model, an overland transport model, and a tightly coupled plant/soil model.

These component models are influenced and logically derived from the SWAT watershed model (which itself is heavily influenced by the EPA QUAL2E model (Brown and Barnwell 1987)) and the EPIC plant growth model.

SOFTWARE DESIGN:

The nutrient modeling code has four components:

- Plant/soil model.
- Overland transport model.
- Channel kinetics and transport model.
- Input/output of nutrient water quality parameters.

This segregated component design does not exist within the implementation of the SWAT and EPIC codes.

Unfortunately, the CASC2D code places its data elements within a single global namespace. All new water quality data variables were declared and marshalled separately from CASC2D. Each of the modules listed above uses a cohesive hierarchal data design with all data elements defined within a C language structure element that corresponds directly to the model it supports. Each model structure element is placed within its own included file. This design eliminates namespace collisions within the preexisting CASC2D data structures and serves to organize and differentiate all water quality data structures.

The approach has been to minimize any modifications to the existing CASC2D model code itself. As the TAPS code exists currently, only a minimum of new subroutine calls have been added to the original CASC2D code.

Following is a description of each component model.

PLANT/SOIL MODEL:

The plant/soil model incorporates the following processes:

- Nitrification (assimilative only).
- Denitrification.
- Nitrogen fixation.
- Volatilization: Nitrogen.
- Mineralization: Nitrogen and phosphorus.

- Immobilization: Nitrogen and phosphorus.
- Mineral P cycling between labile, active, and stable pools.
- Soil temperature modeling.
- Plant potential growth.
- Plant water use.
- Nitrogen uptake.
- Phosphorus uptake.
- Growth constraints based on water, temperature, nutrient, and aeration stress calculations.
- Root growth through an N-layer soil sub-model.

The plant/soil model is driven by a daily time-step. Meteorological data required by the plant/soil model is obtained from the CASC2D data and converted to daily averaged values. The plant/soil module has two primary modes. The first is under dry conditions. During these conditions, only plant-related functions (plant uptake of nutrients, water, and nutrient conversion, as well as microbial activities) are simulated. This is accomplished by utilizing routines within EPIC/SWAT. The second mode is considered during rain events. This mode includes updates to the moisture routing algorithms as well as the overland flow component. As each process is executed during this daily time-step, a constituent mass balance for each soil layer is performed.

During periods of rainfall when soil layer saturation occurs, the portion of constituent mass available for transport by moving water is transferred by code residing in the overland transport model. This implies that nutrients in the pore water are now available for overland flow transport and that vertical transport under saturated conditions continues.

The plant/soil model is executed through a subroutine call from within the CASC2D external time-marching loop. Once CASC2D begins its internal rain processing loop (which may last for a time period greater than a day), execution of the plant/soil model is guaranteed by the placement of another subroutine call within this loop. Code within the plant/soil model forces execution to take place with a daily time-step. The soil infiltration algorithms should logically be placed within the soil component of this model. When this code eventually migrates to GSSHA, a redesign of one or the other may be necessary.

One problem encountered with this project concerns the calculation of soil water infiltration. CASC2D incorporates one method for calculating soil infiltration, while the EPIC code incorporates another. Adapting the EPIC code to CASC2D's infiltration code would have required extensive modifications to the CASC2D code. Furthermore, adapting the EPIC soil moisture calculations to the CASC2D code would likewise require extensive modifications to the EPIC process logic and code. It is important to note that CASC2D has been declared obsolete and is to be replaced by the GSSHA model.[1] However, CASC2D had to be used for this project since the authors did not have access to the latest GSSHA model code which was still under development. During this project, modifications to the existing CASC2D code (version 18) were kept to a minimum. Because of this constraint, the EPIC soil infiltration code was brought into the new water quality code base and the soil infiltration procedure will be unified at a later time when GSSHA code becomes accessible. The

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authors recommend that the EPIC code be modified such that GSSHA infiltration algorithms drive the soil moisture calculations during rainfall events in the future.

OVERLAND TRANSPORT MODEL: The overland transport model transports various forms of dissolved nitrogen and phosphorus between the plant/soil model and the aquatic model. The overland transport model solves the two-dimensional advection-diffusion equation using an implicit two-dimensional finite-difference Peaceman-Rachford ADI numerical technique. The overland cell flow-field generated by the CASC2D code is used to drive the nitrogen and phosphorus species transport within the overland model. After performing the transport process, the constituent mass leaving the overland system is added to the aquatic model's cell source terms using the overland-cell-to-channel-cell linkage information within the CASC2D data structures.

The overland transport model is executed from within the CASC2D rain-event processing loop and utilizes the time-step used by CASC2D at that execution point.

AQUATIC MODEL: The aquatic nutrient process model (based on QUAL2E) includes transport and is based on Monod equations for the following variables:

- Chlorophyll/algae growth/respiration with localized nitrogen/phosphorus uptake limitation.
- Organic nitrogen.
- Ammonium - N.
- Nitrite - N.
- Nitrate - N.
- Organic phosphorus.
- Dissolved phosphorus.
- Carbonaceous BOD.
- Dissolved oxygen.

The overland model described above is a localized source of dissolved nitrogen and phosphorus for the aquatic model. This is accomplished through the CASC2D lateral flow routines during periods of overland flow. The aquatic model executes the nutrient kinetics and transports nutrient mass using a one-dimensional implicit finite-difference numerical integration scheme.

The aquatic model does not implement a heat balance modeling capability. Stream temperatures are calculated through an empirical formula obtained from the SWAT model. Temperature is used to modify the first-order kinetic rate equation coefficients.

The aquatic model is executed through a subroutine call from within the CASC2D external time-marching loop; thus, it is continuously running. Like the plant/soil model, an additional subroutine call to the aquatic model is placed within CASC2D's internal rain processing loop. When the aquatic model is called from either location, it is advanced by the time-step of the enclosing loop. This ensures continuous time simulation.

DISCUSSION: Approximately 50 percent of the code in the CASC2D version used for this project is composed of input and output statements. Watershed models require a large amount of input and

generate copious amounts of output. The addition of water quality modeling capabilities will likewise eventually contribute its share of input-output burden to the code. In the near future, the input code structure for CASC2D/GSSHA will require some modifications to accommodate the large volume of required data.

Unfortunately, the development of the nutrient transformation kinetics and transport processes comprising the water quality capabilities consumed all of the allotted project time. In particular, a considerable amount of time was spent in testing the finite-difference algorithms used to solve the transport equations for the overland and aquatic models and the linkage between the three models. Minor development of the input-output support code base was accomplished during this time.

This software development effort has attempted to use existing CASC2D data files whenever possible. Some of the plant/soil model parameters are currently specified within the code. These should be removed and placed in additional input files. Currently, minimal water quality model output exists.

Additional time on this project would be needed to add all of the input-output capabilities to support the water quality code that has been added to CASC2D. The linkage between the three different models that together constitute the nutrient modeling code also needs to be tested further to verify mass conservation of all species of nitrogen and phosphorus simulated.

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